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Original Article

Safety Evaluation of the Lighting at the Entrance of a Very Long Road Tunnel: A Case Study in Ilam

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ABSTRACT

Background: At the entrance of a tunnel, reflection of sunlight from the surrounding environment and a lack of adequate lighting usually cause some vision problems. The purpose of this study was to perform a safety evaluation of lighting on a very long road in Ilam, Iran.
Methods: The average luminance was measured using a luminance meter (model S3; Hagner, Solna, Sweden). A camera (model 108, 35-mm single-lens reflex; Yashica, Nagano, Japan) was used to take photographs of the safe stopping distance from the tunnel entrance. Equivalent luminance was determined according to the Holliday polar diagram.
Results: Considering the average luminance at the tunnel entrance (116.7 cd/m^2) and using Adrian's equation, the safe level of lighting at the entrance of the tunnel was determined to be 0.7.
Conclusion: A comparison between the results of the safe levels of lighting at the entrance of the tunnel and the De Boer scale showed that the phenomenon of black holes is created at the tunnel entrance. This may lead to a misadaptation of the drivers' eyes to the change in luminance level at the entrance of the tunnel, thereby increasing the risk of road accidents in this zone.

1. Introduction

Health and safety issues associated with the traffic system, such as improving visibility for drivers, has attracted increasing attention in recent years due to the soaring rates of deaths, injuries, and disabilities resulting from road traffic accidents [1]. Traffic accidents in tunnels comprise a small share of total road accidents; however, the human and economic losses associated with tunnel accidents are considerably more severe than those on open roads [2]. The majority of all these accidents occur in the entrance zones of tunnels [3]. In this regard, providing good visual conditions for drivers approaching a tunnel entrance is a crucial factor. Tunnels can be divided into different key areas with regard to planning of lighting. The first zone in the tunnel is called the threshold zone, which is located right after the access zone; this is situated on the open road before the tunnel entrance. The luminance levels of these two areas are directly related to each other [4].

One of the major problems associated with road tunnels is the black hole phenomenon. This phenomenon is due to the reflection of sunlight from the surrounding environment to drivers' eyes, especially on sunny days (see Fig. 1), as well as the lack of adequate lighting at the entrance of tunnels, which reduces the contrast of the barrier at the tunnel entrance and causes some vision problems [5,6]. As a result, the risk of traffic accidents may be increased. When the tunnel entrance has the appearance of a black hole, it reduces the self-confidence of motorists and they may drive in a hesitant manner, negatively affecting traffic safety [4]. Amundsen and colleagues [7] showed that a high percentage of accidents occur in the 50 m before entering a tunnel and the rate of accidents in this zone is several times higher than that at the middle of the

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Fig. 1. Black hole phenomenon at the entrance to a road tunnel.

tunnel. Lidström [8] has reported that in the 150 m before entering the tunnel, drivers' attention is focused on the entrance of the tunnel and almost all of them ignore signs posted near the tunnel.

Due to the problems associated with lighting the entrance zone of tunnels and to reduce the possibility of accidents in these areas, the International Commission on Illumination (CIE) [9] developed the standard CIE 88 in 1990. According to CIE 88-1990, the amount of light required at the beginning of a tunnel has been determined based on the average luminance in the 20° conical field of view to avoid the black-hole phenomenon [10]. In CIE 88 version 2004, the luminance required to prevent the black-hole phenomenon at the entrance to a tunnel was more precisely determined. Studies have revealed that the application of these guides can effectively reduce the incidence of road traffic accidents [11].

Vehicle drivers approaching a tunnel should have enough vision into it from an appropriate distance, so that they are able to react in time if required [12,13]. For this reason, the CIE 88 defines a safe distance as safe-stopping distance (SSD). SSD is a distance in which drivers can see any obstacle in the tunnel entrance and can have an appropriate reaction to and can stop in front of it. This distance is equal to the sum of the perception–reaction distance and the braking distance [14].

Adrian [15] presented a method for the subjective evaluation of lighting at the entrance of tunnels based on the CIE standard. In this study, drivers were in a simulated environment near the tunnel entrances. Participants were requested to assess the quality of light at the entrance for safe entry into the tunnel by the De Boer scale (safety rating numbers) in terms of different intensities of luminance at the entrance of a tunnel (L_{th}), luminance in the surroundings of the tunnel (L_{seq}), and contrast of barriers at the entrance of the tunnel (C). Table 1 demonstrates the De Boer scale for subjective evaluation of the quality of light at the entrance for safe entry into a road tunnel.

Since maintaining satisfactory visual performance in the entrance zone of a tunnel is a crucial factor for the safety of drivers approaching the tunnel [15], the present study aimed to assess the level of safety at the entrance of a very long road tunnel located in Ilam province, Iran. The tunnel has a length of 1,200 m and a width of 10.6 m. The geographical location of the tunnel is shown in Fig. 2.

Table 1
De Boer scale for subjective evaluation of the quality of lighting for safe entry into a road tunnel [3,14]

Subjective scale (SRN)	Criterion	Description
1	Black hole	Completely unacceptable
3	Inadequate, entrance too dark	Entrance too dark, not sufficient for a safe entry
5	Fair, just sufficient for a safe entry	Lower limit of just-sufficient levels for safe entry
7	Good, driver feels safe when entering	Satisfactory, driver feels safe when entering
9	Excellent	Very good viewing conditions

SRN, safety rating number.

Fig. 2. Geographical location of the Azadi Tunnel.

Rows of luminaires (about 3.4 m apart) were mounted in its ceiling. Philips Ceramalux high-pressure sodium lamps were used at the entrance of the tunnel.

2. Materials and methods

The results of subjective tunnel entrance appraisals in Adrian's [15] study are shown in Fig. 3. As can be seen in Fig. 3, the quality of lighting at the entrance of the tunnel has been determined using the subjective response of participants to a safe level of lighting at the entrance of the tunnel, barrier contrast (C), luminance at the entrance of the tunnel or threshold-zone luminance (L_{th}), and the veiling luminance of the surroundings (L_{seq}). Adrian presented an equation [Eq. (1)] to assess the safe level of lighting in the entrance of tunnels by using Fig. 3. In the present study, the quality of lighting at the entrance of the tunnel has been obtained from the safety rating numbers from Eq. (1), and for its description, the subjective De Boer scale was used (Table 1):

$$SRN = 6\left(\frac{\log L_{th}}{L_{seq}}\right) + 4.1 \tag{1}$$

The first step to assess the safety level of lighting at the entrance of tunnels is to determine the average luminance at the entrance of the tunnel (L_{th}). For this purpose, the luminance meter (model S3; Hagner, Solna, Sweden) installed on a stand at the centerline of the road, at the eye height of drivers and at an angle of 1° below the line of sight; luminance was measured in the network center (Fig. 4). Then, luminance in other parts was measured according to

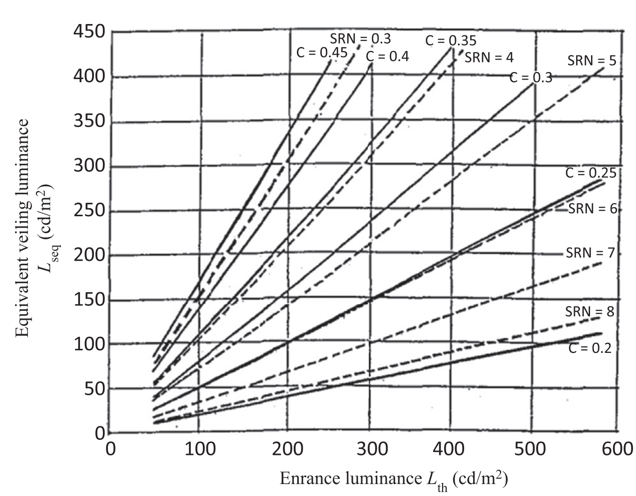

Fig. 3. Subjective assessment of lighting in entrance tunnels [14]. C, target contrast; SRN, safety rating number.

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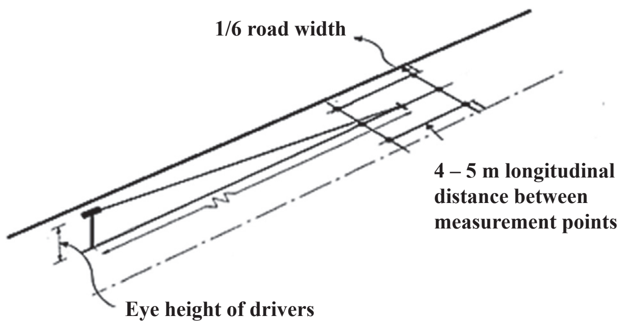

Fig. 4. Measurement of luminance at the entrance of road tunnels. *Note.* Adapted from the standard IESNA-LM-71-1996.

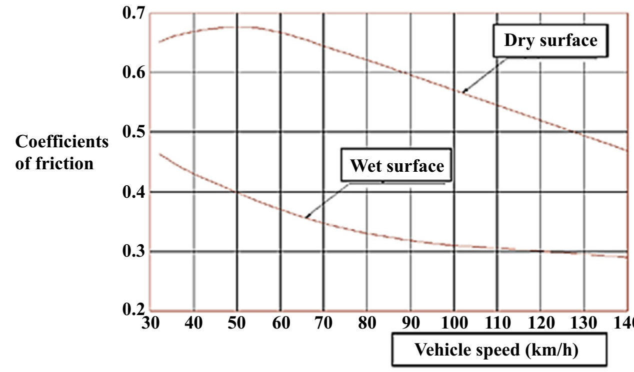

Fig. 5. Determination of the coefficient of friction between road and tire. *Note.* Adapted from the standard CIE-88-2004.

standard CIE 088:2004. The longitudinal distance between measurement points was considered 4 to 5 m and the transverse distance between them was 1/6 road width [11,16,17]. According to the IESNA-LM-71-1996 standard guideline, luminance on tunnel road surfaces can be measured using six test points per traffic lane. These test points are arranged in right, left, and lane-centered pairs that form a rectangle. A tripod-mounted luminance meter is placed at a distance of 83 m from the midpoint of this rectangle. The right and left boundaries of this rectangle run inside the traffic lane (at 1/6th the traffic lane width and parallel to lane edges), and contain the right and left test points, respectively (Fig. 4) [16,17].

For calculating the veiling luminance, L_{seq}, due to scattering of light in the eye from bright tunnel surroundings [4], the first step is to determine the SSD. It is made up of four components: human perception time, human reaction time, vehicle reaction time, and vehicle braking capability [18]. The scientific definition of a safe-stopping distance is sum of the distance between the time when someone decides to stop a vehicle moving, and the time when the vehicle completely stops or it defines as sum of the distance between the processing for obstacle detection in the brain and the brake reaction; so that, this distance avoid hitting the car to possible obstacles [14].

The SSD (m) is an important factor in the design of lighting in tunnels, which depends on several factors, including road gradient (upward or downward; $\pm s$, %), passing vehicle speed limit (U, m/s), driver reaction time (t_0, s), acceleration due to gravity (g, m/s^2), and the coefficient of friction between the tire and the road (f, dimensionless). The SSD is calculated based on Eq. (2):

$$\mathrm{SSD} = U \times t_0 + \frac{U^2}{2 \times g \times (f \pm S)} \tag{2}$$

The coefficient of friction between the tire and the road (f), which depends on the vehicle speed and the road surface (dry or wet), is determined using the graphs shown in Fig. 5.

L_{seq} can be determined by two methods: direct and indirect. In the direct method, L_{seq} was measured according to the Holladay [19] formula, using a field luminance meter. However, the indirect method that was used in the present study was performed by a camera (model 108, 35 mm single-lens reflex; Yashica, Nagano, Japan). This camera can cover the SSD approximately 56° horizontally and 38° vertically. After taking photographs of the entrance of the tunnels, the Holladay polar diagram is drawn on the picture (Fig. 6), scaled from the perspective of the SSD. Luminance of each sector of the diagram was determined considering the driving direction and the type of environment around the tunnel (Table 2) [4].

It is notable that the Holladay polar diagram consists of nine rings and each ring is divided into 12 sectors; the angle of each ring is shown in Table 3.

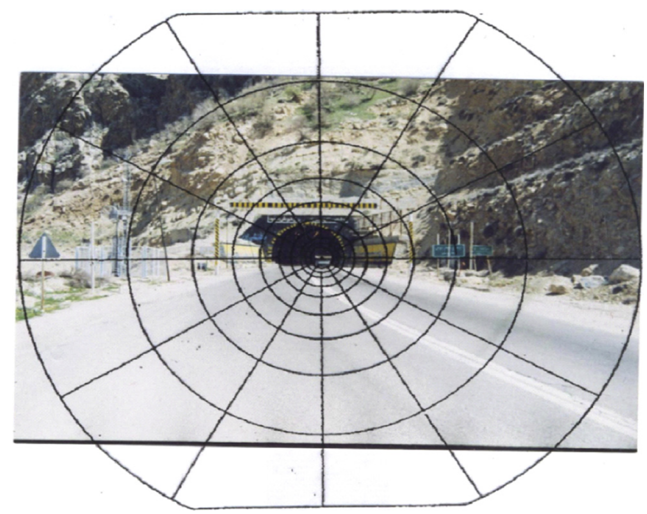

Fig. 6. Sketch of a polar grid.

Table 2
Luminance value in each sector of the Holladay polar diagram

Driving directions (in the northern hemisphere)	Luminance of the sky (kcd/m^2)	Luminance of the road (kcd/m^2)	Luminance of the surrounding environment of the tunnel (kcd/m^2)		
			Rock	Building	Grass
North	8	3	3	8	2
East–west	12	4	2	6	2
South	16	5	1	4	2

The total veiling luminance L_{seq} [Eq. (3)] is then obtained by summing the contributions from all segments [4]:

$$L_{seq} = \left(5.1 \times 10^{-4}\right) \times \sum L_{segment\ i} \tag{3}$$

3. Results

In this study, the eye height of Iranian drivers was determined to be 131 cm [20], and the measurement was taken from the seat

Table 3
Angles of each ring of the Holladay polar diagram

Ring	Central	1	2	3	4	5	6	7	8	9
Degree	2	3	4	5.8	8	11.6	16.6	24	36	56.8

Fig. 7. Placement of a barrier at the entrance of tunnels at specified points.

height of the conventional vehicles in the country. Since installation of the luminance meter at an angle of 1° below the line of sight was difficult and sometimes impossible, trigonometric relationships were used to facilitate the measurement. The distance between the central measurement points and drivers was determined 75 meters. According to CIE standard recommendations, to prevent natural light interference at the tunnel entrance, measurements were performed after sunset. As can be seen in Fig. 7, a barrier was placed at specified points at the entrance of the tunnel; the luminance meter was then installed at a height of 131 cm and a distance of 75 m from the central point of measurement. As shown in Fig. 4, luminance was measured at the marked points at the entrance of the tunnel. After measuring the luminance in all regions, the average luminance at the tunnel entrance was calculated to be approximately 31.7 cd/m^2.

The International Lighting Committee recommended that the reaction time of drivers, which is a necessary factor for calculating the SSD and so the equivalent luminance, should be considered based on studies performed in the country [9]. A study by Alimohammadi et al [21] found that the reaction time for drivers is 0.69 seconds, using a driving simulator. It has been suggested that, while designing lighting in road tunnels, road surface can be considered wet for places where rainfall occurs on average over 75 hours per year [22]. According to the 10-year meteorological data from the weather station 40780 Ilam, rainfall occurred on average 73.8 days per year. As a result, the road surface was considered wet. Using Fig. 5, the coefficient of friction between the road and the tire was determined to be 0.35. Therefore, the SSD at the entrance of the tunnel was calculated to be 56 m [see Table 4 and Eq. (2)].

The photos were taken from the entrance to the tunnel in safe-stopping distance and at a height of 131 cm (Fig. 6). By drawing the Holladay polar diagram on the pictures and using the grid in any part of the sector, the percentages of environmental factors (rock, grass, roads, etc.) were determined. According to Table 2, the luminance value in each sector was found. Note that, as can be seen in Table 5, luminance was not calculated in some parts of the outer sector; CIE standard expressed that in these sectors the dashboard and the roof of the vehicle prevent the brightness from reaching the drivers' eyes [9].

The total veiling luminance, L_{seq}, was 116.7 cd/m^2, based on Table 5 and Eq. (3). According to the luminance (L_{th}) and equivalent luminance (L_{seq}) of the tunnel entrance, the safe lighting level

Table 4
Variables in determining the safe-stopping distance

Driving directions	Maximum speed of vehicle (m/s)	Slope of road	Reaction time (s)	Coefficient of friction
Northern line tunnel entrance	18	+0.03	0.69	0.35

Table 5
Luminance values of the tunnel under study in each sector of the Holladay polar diagram

Sector	Ring								
	1	2	3	4	5	6	7	8	9
1	1.5	3	3	3	3	3	3	3	–
2	0	3	3	3	3	3	3	3	3
3	0	0	5.5	5.5	3	3	3	3	3
4	0	0	0	8	8	5.5	3	3	3
5	0	0	0	0	2.4	3	3	3	3
6	0	0	0	0	2.4	3	3	2.5	–
7	0	0	0	0	2.1	3	3	2.5	–
8	0	0	0	0	0.3	1.8	3	3	3
9	0	0	0	0	0	3.5	3.5	3	3
10	0	0	0	1.5	3	3	3	3	2.8
11	1.5	3	3	3	3	3	3	3	3
12	3	3	3	3	3	3	3	3	–
Luminance of each ring (kcd/m^2)	6	12	17.5	27	33.2	37.8	36.5	35	23.8
Total luminance (kcd/m^2)	228.8								

(safety rating numbers) was determined to be 0.7, which is comparable to the De Boer scale results (Table 1); it can be concluded that the phenomenon of black holes is created at the entrance of the tunnel under study.

4. Discussion

Tunnels have an important role in the transportation network of Iran, especially in its mountain regions and crowded cities. The lighting level in the threshold zone of a tunnel should match the adaptation level of drivers' eyes [23].

For drivers approaching a tunnel, the contrast of tunnel obstacles is decreased because of the luminance distribution of the tunnel surroundings in their field of view, and so their ability to see obstacles in the tunnel is reduced, resulting in the creation of the black hole phenomenon. Some studies have indicated that the black hole phenomenon leads to uncertainty in drivers' decision-making while approaching a tunnel [10,24]. The severity of injuries resulting from accidents at the tunnel entrance is greater than those occurring on highways [12,25].

The driver must be able to detect other cars in the tunnel and also identify obstacles as soon as possible to allow sufficient time for reaction. High luminance levels can create a glare, thus leading to an increased risk of accidents and endangering the safety of drivers.

The results showed that the black hole phenomenon is created at the entrance of the tunnel under study. This may significantly increase the risk of traffic accidents at the tunnel entrance. Decreasing the luminance and increasing the lighting in the threshold zone of the tunnel can reduce this phenomenon. Some studies have offered solutions to reduce the phenomenon of black holes. For example, Onaygil et al [5] found that planting trees and painting the surfaces around the tunnel with dark colors could remarkably reduce the luminance at the tunnel entrance.

The use of an asymmetric luminaire that distributes the light in the opposite direction of the vehicle can increase the brightness level of the road surface and reduce barrier brightness, thereby increasing the visibility of barriers at the entrance to the tunnel [12,25]. In the tunnel under study, a symmetrical lighting system was used, so the road surface and obstacles were equally illuminated. This reduces the contrast between the obstacle and the road surface. However, asymmetric lighting systems may have some disadvantages such as glare and flicker effects, which can lead to problems especially in epileptic drivers [12,25].

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Porous asphalt (ZOBA) was used at the entrance of the tunnel under study. Several studies showed that the road pavement at the entrance of tunnels is important as a background for obstacles. Martens et al [12] showed that asphalt ZOBA decreases the contrast of the asymmetric luminaire, so this type of asphalt is not recommended at the tunnel entrance. Recently, there were concerns about high electrical energy consumption at the tunnel entrance [23,24]. Hence, laboratory research has been conducted to install semitransparent layers outside the entrance to a road tunnel. In this way, in addition to improving the safety level at the tunnel entrance, reduced energy consumption, increased equipment maintenance, and reduced environmental damage can be achieved [26]. García et al [27] found that installation of a semitransparent layer near the tunnel entrance can decrease energy consumption by over 70%. In addition to this feature, semitransparent layers could lead to better and faster adaptation of the driver's eyes to the darkness of tunnels.

The importance of the pavement materials in the inter-reflected light and reducing the electric energy consumption was investigated by Moretti et al [28]. They found that concrete pavement surface is whiter and more reflective than asphalt pavement.

For lighting-specification purposes in the tunnels, the role of the doing preventive measures during the construction process cannot be ignored. Onaygil et al [5] found that the required illumination level in the threshold zone of a tunnel can be significantly decreased by adopting the following structural measures: paying more attention to east or west entrances of a tunnel; considering a rough surface in dark color for all portal surfaces and road pavements in the access zone; covering the surroundings of tunnels with green plants, trees, shrubs, etc.; controlling the speed of vehicles approaching tunnels; and constructing high retaining walls flanking the road using rough and dark materials. Recently, light-emitting diode light sources have attracted the interest of designers and manufacturers as a new lighting system in tunnels. Researchers introduced light-emitting diodes as the most efficient available technology with high levels of optical comfort, long life, reduced energy consumption, green technology, no UV and CO emissions, little infrared light emission, and good color rendering [28,29]. In this study, the level of safe lighting at the entrance of a tunnel was determined. Comparing the results with the De Boer scale, it has been found that the light generated from artificial sources at the entrance to a tunnel was not able to avoid the phenomenon of black holes. This may lead to misadaptation of drivers' eyes to the change in luminance level at the entrance of the tunnel and thereby increasing the risk of road accidents in this zone. To avoid the occurrence of a black hole phenomenon at the entrance of a tunnel, preventive measures can be adopted, such as planting trees, painting tunnel surfaces with low-reflection-coefficient colors, installing asymmetrical LED lights rather than high-pressure sodium or low-pressure sodium and mercury vapor lamps, choosing appropriate road pavement materials, and using semitransparent surfaces near the entrance of the tunnel.

Conflicts of interest

The authors declare no conflicts of interest.

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